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RESEARCH ARTICLE (PEER-REVIEWED)

Embodied Carbon and Construction Cost Differences between Hong Kong and Melbourne Buildings

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Abstract

Limiting the amount of embodied carbon in buildings can help minimize the damaging impacts of global warming through lower upstream emission of CO_2. This study empirically investigates the embodied carbon footprint of new-build and refurbished buildings in both Hong Kong and Melbourneto determine the embodied carbon profile and its relationship to both embodied energy and construction cost. The Hong Kong findingssuggest that mean embodied carbon for refurbished buildings is 33-39% lower than new-build projects, and the cost for refurbished buildings is 22-50% lower than new-build projects (per square metre of floor area). The Melbourne findings, however,suggest that mean embodied carbon for refurbished buildings is 4% lower than new-build projects, and the cost for refurbished buildings is 24% higher than new-build projects (per square metre of floor area). Embodied carbon ranges from 645-1,059 $kgCO_2e/m^2$ for new-build and 294-655 $kgCO_2e/m^2$ for refurbished projects in Hong Kong, and 1,138-1,705 $kgCO_2e/m^2$ for new-build and 900-1,681 $kgCO_2e/m^2$ for refurbished projects in Melbourne. The reasons behind these locational discrepancies are explored and critiqued. Overall, a very strong linear relationship between

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embodied energy and construction cost in both cities was found and can be used to predict the former, given the latter.

Keywords

embodied energy, embodied carbon, construction cost, energy-cost relationship, Hong Kong, Melbourne

Introduction

The benefits of preserving existing buildings are generally well accepted (Jackson, 2005). Socially, these projects help to maintain continuity of a community's history and culture for future generationsto enjoy, as well as safeguard against premature obsolescence or unnecessary demolition of building stock. Environmentally, these projects lessen the demand for new resources bycareful reuse or recycling, minimizewaste sent to landfill and 'reclaim' carbon already invested in existing work (Pomponi and Moncaster, 2018). Economically, these projects should cost less than new-build, however this depends on factors such as the extent of conservation works, the latent conditions of the project and the complexities involved in construction. So, there are sound arguments for why conservation of buildings is important.

Embodied carbon is the invisible part of any building's energy profile. In reality, more focus is applied to a building's operational energy performance using various rating tools and calculators that are commercially available in the international marketplace. Yet many previous studies have concluded that the embodied component can be significant (e.g. Treloar, 1994; De Wolf, Pomponi and Moncaster, 2017; Luo, Yang and Liu, 2016; Zhang and Wang, 2017; Kumanayake, Luo and Paulusz, 2018). Hence, using materials for building construction that possess low embodied carbon intensity can assist, indirectly, to mitigate some of the damaging effects of future climate change resulting from global warming and sea level rise. These effects can be traced back to human-induced carbon emissions entering into the earth's atmosphere, much of which arises from electricity generation using fossil fuels. Minimizing our use of carbon is a fundamental socio-political strategy that the majority of nations globallyhave agreed to uphold (IEA, 2016), at least in principle.

This research aims to compare embodied carbon footprints for a range of new-build and refurbished projects representing a range of functional purposes in both Hong Kong and Melbourne. Refurbished projects are defined as those where the majority of the structure of an existing building is retained and may include change of use. While the Hong Kong projects represent new data, the performance of these projects is to be compared to earlier work undertaken by Langston (2006) based on thirty commercial buildings in Melbourne that also comprised new-build and refurbished work.

The initial research idea arose as part of a Hong Kong RGC-GRF grant (2015-2017) as later acknowledged in this paper. Hence, Hong Kong was chosen as the site for new data collection. Hong Kong is one of the most densely populated cities in the world per square metre of land area, and comprises a dynamic melting pot for new construction, urban renewal, heritage protection and demolition activities (Chan and Lee, 2009).

The decision to compare Hong Kong with Melbourne is to highlight the problems implicit with inter-country comparisons. In this case, these problems are primarily a factor of different energy generation profiles, different approaches to building construction that would engender a different profile of materials and associated energy intensities, and different currencies for estimating building costs. Utilizing the same approach for measuring embodied carbon per square metre of floor area, it would be interesting to know whether both cities also yield similar results. These are compared for both new-build and refurbished construction project types.

This is an empirical study (Fellows and Liu, 2015). The researchers act as impartial 'observers'. The accuracy of the base data (quantities of building work and their unit costs) for each building is not in question. Due to client confidentiality, data are de-identified and contextual information that might have been available from physical site visits and inspections is unfortunately not available.

This study does not test or generate theory, but rather applies current understanding of embodied carbon principles to explore what differences in the relationship between carbon and cost might exist for new-build and refurbished projects in both Hong Kong and Melbourne. This appears a valid research question. The inclusion of Melbourne as a comparator is largely made on convenience of access to detailed data, albeit about ten years earlier than the data collected for Hong Kong. Nevertheless, when making comparisons, energy intensities do not change significantly over time, and within each country any errors in their accuracy largely cancel out to leave exposed the overall differences between the embodied carbon appetites of these two cities in relation to building works.

The structure of the remainder of this paper explores the underpinning literature, which is focused on recent research outcomes relevant to embodied carbon footprints in Hong Kong and Melbourne, an explanation of the method applied, case study results, discussion and limitations, and finally a conclusion and funding acknowledgement.

Underpinning Literature

RICS (2014:5) defines embodied carbon (EC) as:

> *Carbon emissions associated with energy consumption (embodied energy) and chemical processes during the extraction, manufacture, transportation, assembly, replacement and deconstruction of construction materials or products. Embodied carbon can be measured from cradle-to-gate, cradle-to-site, cradle-to-end of construction, cradle-to-grave, or even cradle-to-cradle. The typical embodied carbon datasets are cradle-to-gate. Embodied carbon is usually expressed in kilograms of CO_2e per kilogram of product or material.*

The cradle-to-gate system boundary includes all the upstream carbon requirements for completion of work constructed on site. However, it specifically excludes any operational (recurrent) carbon footprints, such as those arising from heating, ventilation, air-conditioning and cooling systems and all carbon-based electricity required to power machines and building technologies. It also excludes the carbontransactions involved in demolition and removal or recycling at end-of-life.

Carbonemissions areseen as a driver for global warming and climate change (Abergel, Dean and Dulac, 2017; United Nations, 2016). EC is distinct from embodied energy (EE), which may comprise carbon-based or non-carbon-basedfuel sources (e.g. fossil fuels versus renewables). Electricity is the main power source for construction, although a small proportion is attributable to direct use of combustible fuels like diesel and oil.

The analysis of EC is based on the concept of life cycle assessment (LCA). LCA is a techniqueused to evaluate the impacts of a product, technology or service on its surrounding environment. Life cycle includes the stages of raw material extraction, manufacture, transport/ distribution, construction, usage, maintenance and end-of-life scenarios like replacement, disposal or recycling. The term 'embodied' refers to the resource implications of upstream processes that form part of the finished product, technology or service required (Langston, 2005).

Measurement of EC is the dominant approach today, but EE is still in use and was employed almost exclusively prior to the early part of the 21st Century (RICS, 2014; CLF, 2017). The conversion from EE to EC is based on the fuel mix involved in energy generation, and this varies according to location. A country that uses only clean renewable energy, for example, has little interest in EC other than what they import from other carbon-based economies. As a means of mitigating the damaging effects of climate change, countries need to minimize theirongoing use of carbon-based fuels.

CLF (2017) is the largest study to date on embodied carbon in buildings. It is a global study containing over one thousand buildings across a wide range of typologies and incorporates new-build and refurbished projects. It presents EC ($kgCO_2e/m^2$) data and draws conclusions across the entire dataset. Figure 1 summarizes the analysis of the Embodied Carbon Benchmark Database (ECBD) and is used later as a benchmark against which the results in this paper can be compared.Prior to ECBD, the construction industry has seen few efforts to benchmark EC. Some include the Athena Report for Incorporating Whole Building LCA Benchmarks into the IE4B, the European SuPerBuildings Project, the Australian Materials and Buildings Products Life Cycle Inventory Database, and the French "Construisons Ensemble HQE Performance" (CLF, 2017). The mean is shown at about 400 $kgCO_2e/m^2$.

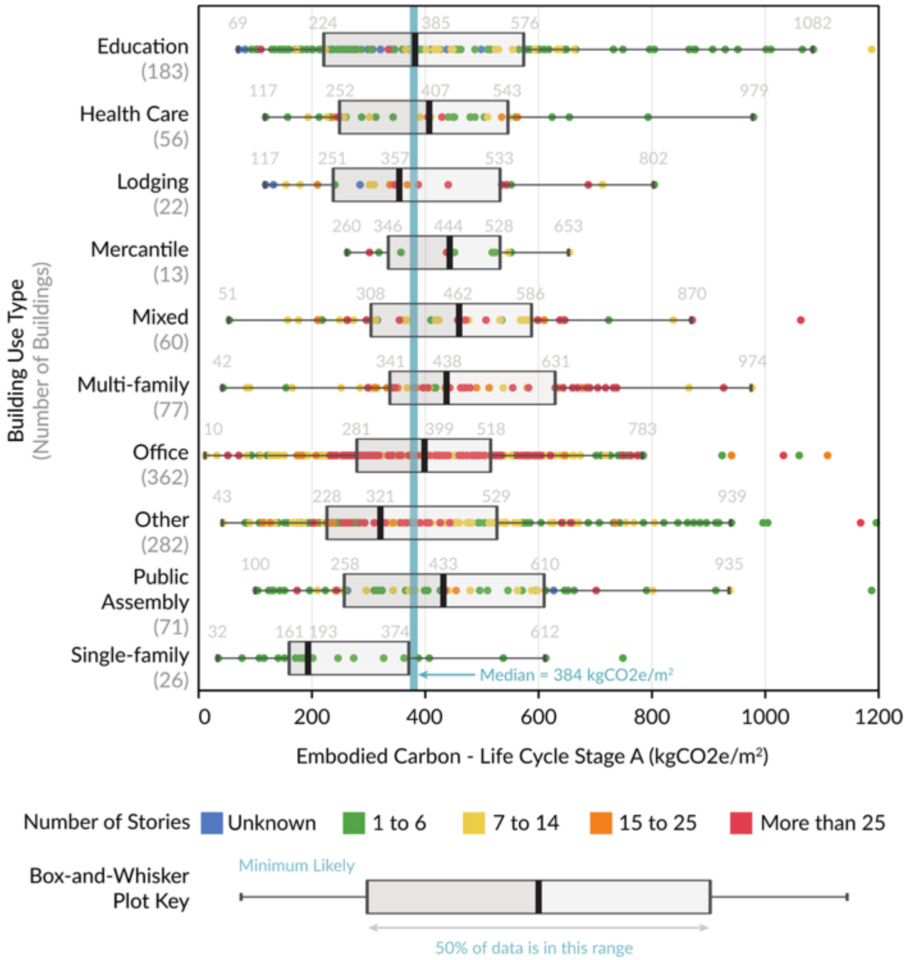

Figure 1. ECBD findings (Source: Simonen, Rodriguez and De Wolf [2017] – reproduced with permission of lead author)

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The main source of relevant embodied energy data pertaining to Hong Kong was found in Chen, Burnett and Chau (2001). However, this data is not actually specific to Hong Kong, but is an average of data from a range of global sources. The same can be said for other Hong Kong research conducted by Chau et al. (2007; 2012; 2015). A comparison between data from Chen, Burnett and Chau (2001) and the ICE database (Hammond and Jones, 2011) shows some consistency on key materials, and appears more reliable. In fact, Chau et al. (2012:33) noted "*since embodied energy data are not specifically collected by national agencies, the data used for estimating the CO_2 emissions in buildings are generally extracted from multiple sources and may not be of good quality*".

The latest EE research for Hong Kong can be found in Chau et al. (2017). They list EE intensities (11 common materials only) from a range of sources including Hammond and Jones (2011). They acknowledged that a majority of building materials in Hong Kong are imported from Mainland China, but a lack of EE data for virgin and recycled building materials also exists there. Using Hammond and Jones (2011) as a basis, they adjusted EE intensities for assumed transportationenergies both within China and from China to Hong Kong. However, constructing a more reliable database of EE intensities suitable for use in both Mainland China and Hong Kong SAR is a recommended area of further research (Pan, Qin and Zhao, 2017).

Langston (2006) studied the EE implications for thirty individual buildings in Melbourne through discovering and quantifying a reliable linear relationship with construction cost data. From this relationship, EE could be calculated knowing only the estimated cost of construction and the gross floor area. The method underpinning the study was set out in Treloar (1994).

Gan et al. (2017a) found that EC mapped against number of storeys (40-100) produced an upward concave curve, suggesting an optimum building height can be determined. However, this study was based on a geometric model of a typical high-rise building and did not use real data. Wu, Peng and Lin (2017), based on a study of 26 actual residential and commercial buildings in China, found that green (ESGB-certified) buildings had slightly higher EC/m^2 than non-green buildings, but with much lower operational emissions, and this phenomenon was significant in residential buildings. Gan et al. (2017b) found that structural steel and rebar accounted for the majority of EC in the frame of high-rise buildings in Hong Kong.

Chau et al. (2000) investigated the cost of the HKBEAM environmental rating scheme for Hong Kong. They found that the economic benefit-cost ratios of prescribed criteria under the [then]HKBEAM structure varied considerably. Lam et al. (2010) analysed 25 commercial buildings in Hong Kong, including three Grade A office buildings, four Grade B office buildings, one Grade C office building, four retail centres and three hotels. They found no statistical differences in the average life cycle environmental impacts for different building types. However, concrete, reinforcement bar, and copper cables and busbars were ranked to be the most significant materials or components to total life cycle environmental impacts. In a later study, Lam et al. (2011) called for a framework for developing green specifications to promote sustainability in Hong Kong.

Finally, Ng and Chau (2015) looked at different waste management strategies and found that recycling had the highest energy saving potential for EE (53%), compared to reusing (6.2%) and incineration (0.4%).

Method

This research uses a case study methodology (Yin, 2017). For each case, a list of building materials and quantities (such as may be found in a cost plan) is required. ECcan be derived from this list, based on embodied energy intensities and carbon-based fuel mix, including all the upstream carbon implications involved in mining, manufacture, transport and installation onsite, and expressed in $kgCO_2e/m^2$ of construction floor area (CFA) in Hong Kong or gross floor area (GFA) in Australia. CFA and GFA are similar enough to not require re-measurement. The Australian data werenot collected as part of this research butwere reported in Langston and Langston (2007). EC performance was not computed in that study, although EE data was provided using a hybrid input-output calculation model (Lenzen and Murray, 2001; Treloar, 1994). All construction costsare expressed in 2016 terms in local currency per square metre of floor area (note that Melbourne costs were escalated by 38.7% to convert themfrom 2005 to 2016).

RICS (2014) provides useful guidance for undertaking EC calculations. Yet it does not make it clear that EC intensities vary according to the mix of energy generation strategies in different countries, and that this mix changes over time. Countries are aiming to reduce their use of carbon for generating electricity, which accounts fora largeamount of EE involved in upstream manufacturing processes for materials and other building components. In this study, EE will first be estimated using energy intensities (ultimately expressed in GJ/unit), as EE is not as volatile as EC over time. Then EC will be calculatedbasedon the currentfuel mix used in electricity generation for a particular location, which is time-sensitive.

Environment Bureau (2014) discusses future power generation options for Hong Kong and forms the basis for a suitable current EE-EC conversion factor for use in this study. Note that this is significantly higher that the factor estimated by Chau et al. (2012). The factor is forecast to reduce over time (see Table 1).It may be appropriate to use China's energy mix instead, since most of Hong Kong's material resourcescomefrom across the border. If so, the conversion factor should be 69.40 $kgCO_2e/GJ$, which is 18.07% higher than the current mix in Hong Kong (Greig, 2016).In this study, however, it was decided to use Hong Kong's fuel mix. Comparative data for Australia is also shown in Table 2 (the forecast for 2025 is aspirational).

Table 1 Hong Kong electricity generation mix

Generation Type	Now (2012)	Emission Factor ($kgCO_2e/GJ$)	Future (2023)	Emission Factor ($kgCO_2e/GJ$)
Coal-fired power	53%	89.60	20%	89.60
Natural gas	22%	51.33	60%	51.33
Nuclear	23%	0.00	20%	0.00
Others	2%	0.00		
Fuel mix:		58.78		48.72

The research plan in this studywas to approach a number of prominent quantity surveying consultancies in Hong Kong to request data in the form of cost plans. Projects had to be evenly distributed between new-build and refurbishedworks, and no more than five years old. Ideally thirtyprojects in total were sought. This proved to be quite difficult due to client confidentiality concerns. There were no historic buildings in the dataset.

Table 2 Australia electricity generation mix – source: Langston (2015)

Generation Type	Now (2015)	Emission Factor ($kgCO_2e/GJ$)	Future (2025)	Emission Factor ($kgCO_2e/GJ$)
Coal-fired power	36%	89.60	30%	89.60
Metallurgical coal	8%	92.78	5%	92.78
Gas-fired power	6%	51.33	10%	51.33
Gas heating	9%	52.07	10%	52.07
Oil	28%	65.34	20%	65.34
Renewables	14%	0.00	25%	0.00
Fuel mix:		65.07		54.93

From the items of work within these cost plans, material quantities were converted to mass (kg) and multiplied by EE intensities. Total EE, expressed in gigajoules (GJ), was computed as the sum of all the materials in the project via a spreadsheet application. A cradle-to-gate approach was adopted. Upon completion, the total EE was converted to EC using the current fuel mix data from Table 1 (earlier). The construction cost was taken directly from the cost plan and updated to 2016 prices where necessary, using RLB (2017) building price index (BPI). The CFA was also taken directly from the cost plan, and used to compare Cost, EE and EC per square metre of total floor space.

As noted earlier, there are no EE intensities unique to Hong Kong. However, Chen, Burnett and Chau (2001) published a list of common building materials with EE intensities expressed in MJ/kg as part of research into Hong Kong residential buildings. These were preferentially used as the basis for the calculations in this study. Where other materials were encountered, these were computed using a combination of similar items, and where this was unrealistic, from EE data sources in other countries, including the ICE database (Hammond and Jones, 2011). The latter was also very useful for converting measured units of m^3, m^2, m, etc. to kilograms for each material.

De Wolf, Pomponi and Moncaster (2017), in a large study of the global practice of embodied carbon modelling for built environment applications, concluded that governments should mandate for improved data quality as well as support the development of a more transparent and simplified methodology.

As stated earlier, the Melbourne data and applied methodology were derived from Langston (2006). Her study comprised thirty commercial buildings of various functional types. Detailed EE calculations based on consultant quantity surveyor cost plan quantities and unit rates were used to compile the results, which are summarized in this paper. EC was not undertaken in her original research, and hence was an extension in this paper. Costs were updated from 2005 to reflect 2016 prices (i.e. 36.89% increase) using the BPI in Rawlinsons (2017).

Case Study Results

With the valued cooperation of several large quantity surveying consultancies in Hong Kong SAR and Mainland China, 26 project cost plans were eventually attained and used to perform all the necessary calculations to determine EE. They were effectively a random sample of recent Hong Kong projects. The cost plans comprised 14 new-build projects and

12 refurbished projects. Of the 14 new-build, all of which were designated as high-quality residential apartments by the consultants, two were actually low-rise residential projects. They were treated as outliers as they were less efficient in key elements such as foundations, roof and external envelope and hence hadmuch higher Cost/CFA values. Of the 12 refurbished projects, all of which were designated as high quality low/medium-rise office space except one high quality high-rise apartment, only seven involved significant structural work. Unfortunately, fourprojects involved mainly decorative upgrades. One of the refurbished office projects had to be rejected as it was confined to façade replacement and did not relate to a measurable floor area at all.

Tables 3 and 4 list the results of the new-build and refurbished projects for Hong Kong respectively. Projects 4, 10, 21 and 24-26 were later excluded as outliers, and Project 23 was rejected since it could not be used. That left 19 projects for further analysis.

Table 3 New-build projects (Hong Kong)

ID	CFA	Cost	EE	EE/CFA	EC/CFA	Cost/CFA	Comment
1	25,477	588	362,195	14.22	836	23,093	
2	107,663	3,750	1,181,816	10.98	645	34,835	
3	19,735	748	222,860	11.29	664	37,880	
4	17,901	1,097	257,327	14.38	845	61,271	low-rise
5	164,533	4,827	1,910,130	11.61	682	29,339	
6	384,137	14,165	4,430,499	11.53	678	36,875	
7	53,969	2,000	723,626	13.41	788	37,067	
8	240,846	6,963	2,929,006	12.16	715	28,912	
9	146,775	6,689	2,644,634	18.02	1,059	45,574	
10	15,785	1,236	235,325	14.91	876	78,277	low-rise
11	48,496	2,113	533,310	11.00	646	43,570	
12	74,292	2,532	968,524	13.04	766	34,086	
13	192,047	6,749	2,439,680	12.70	747	35,145	
14	179,725	6,365	2,170,321	12.08	710	35,415	
			Mean:	12.95	761	40,096	
Notes:							
CFA = construction floor area (m^2)							
Cost = HKD (millions)							
EE = embodied energy (GJ)							
EC = embodied carbon ($kgCO_2e$)							
EE→EC conversion = 58.78 $kgCO_2e$/GJ							

Table 4 Refurbished projects (Hong Kong)

ID	CFA	Cost	EE	EE/CFA	EC/CFA	Cost/CFA	Comment
15	23,161	253	115,684	4.99	294	10,905	
16	28,150	992	257,119	9.13	537	35,236	
17	2,900	158	26,009	8.97	527	54,410	
18	4,712	107	38,376	8.14	479	22,784	
19	4,800	64	46,299	9.65	567	13,300	
20	24,490	571	183,204	7.48	440	23,316	
21	275	3	2,095	7.62	448	11,891	decorative
22	18,294	577	203,727	11.14	655	31,557	
23	n/a	71	4,199	n/a	n/a	n/a	façade
24	610	3	3,485	5.71	336	5,082	decorative
25	10,155	13	70,617	6.95	409	1,325	decorative
26	4,010	35	29,741	7.42	436	8,728	decorative
			Mean:	7.93	466	19,867	
Notes:							
CFA = construction floor area (m^2)							
Cost = HKD (millions)							
EE = embodied energy (GJ)							
EC = embodied carbon ($kgCO_2e$)							
EE→EC conversion = 58.78 $kgCO_2e/GJ$							

Thanks to the cooperation of the original researcher, the Melbourne dataset was split into 19 new-build and 11 refurbished projects. EC was computed by multiplying values of EE by 65.07 $kgCO_2e/GJ$, using information sourced from Langston (2015). Tables 5 and 6 list the results of these new-build and refurbished projects respectively. No outliers were evident.

Table 5 New-build projects (Melbourne)

ID	GFA	Cost	EE	EE/GFA	EC/GFA	Cost/GFA	Comment
1	1,409	4	26,742	18.98	1,235	2,887	
3	1,791	5	36,679	20.48	1,333	2,867	
4	2,543	8	60,326	23.72	1,544	3,164	
6	6,761	26	154,157	22.80	1,484	3,799	
7	328	1	7,275	22.18	1,443	2,212	
8	1,223	3	21,397	17.50	1,138	2,147	
11	249	1	5,991	24.06	1,566	2,923	

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Table 5 continued

ID	GFA	Cost	EE	EE/GFA	EC/GFA	Cost/GFA	Comment
12	635	2	15,696	25.11	1,634	3,449	
13	2,696	6	49,445	18.34	1,193	2,040	
14	2,790	11	62,048	22.24	1,447	3,797	
16	378	2	9,261	24.50	1,594	4,008	
18	5,412	7	105,937	19.57	1,274	1,378	
19	4,281	17	112,160	26.20	1,705	4,043	
20	787	2	18,322	23.28	1,515	3,135	
21	1,159	4	28,008	24.17	1,572	3,571	
24	10,565	47	263,068	24.90	1,620	4,461	
28	2,502	8	57,218	22.87	1,488	3,121	
29	5,223	17	96,058	18.39	1,197	3,325	
30	3,649	12	78,622	21.55	1,402	3,233	
			Mean:	22.15	1,441	3,135	
Notes:							
GFA = gross floor area (m^2) – similar to CFA							
Cost = AUD (millions)							
EE = embodied energy (GJ)							
EC = embodied carbon ($kgCO_2e$)							
EE→EC conversion = 65.07 $kgCO_2e$/GJ							

Table 6 Refurbished projects (Melbourne)

ID	GFA	Cost	EE	EE/GFA	EC/GFA	Cost/GFA	Comment
2	450	2	9,571	21.27	1,384	3,595	
5	528	1	9,558	18.10	1,178	2,150	
9	3,278	16	77,893	23.76	1,546	4,849	
10	3,760	20	96,512	25.67	1,670	5,362	
15	5,677	22	134,281	23.65	1,539	3,945	
17	652	2	10,405	15.96	1,038	2,691	
22	12,930	60	286,656	22.17	1,443	4,678	
23	18,821	56	260,255	13.83	900	2,983	
25	4,704	23	121,541	25.84	1,681	4,958	

Table 6 continued

ID	GFA	Cost	EE	EE/GFA	EC/GFA	Cost/GFA	Comment
26	1,345	4	24,983	18.57	1,209	3,043	
27	5,940	26	149,738	25.21	1,640	4,340	
			Mean:	21.28	1,384	3,872	
Notes:							
GFA = gross floor area (m^2) – similar to CFA							
Cost = AUD (millions)							
EE = embodied energy (GJ)							
EC = embodied carbon ($kgCO_2e$)							
EE→EC conversion = 65.07 $kgCO_2e/GJ$							

For Hong Kong, after removing the outliers noted earlier, a very strong relationship is found between EE and Cost for new-build (N) projects. An r^2 of 0.9573 shows that EE (or EC) can be reliably predicted from Cost using Eq.1. Refurbished (R) projects are shown to also have a very strong relationship between EE and Cost. An r^2 of 0.8912 shows that EE (or EC) can be reliably predicted from Cost using Eq.2. High r^2 values indicate that a good fit of x and y values – in this case, total cost and total energy respectively. Both equations for Hong Kong are provided below – where Cost is measured in HKD (millions):

$$EE_N = 346.77 \times Cost \qquad \text{(Eq.1)}$$

$$EE_R = 296.23 \times Cost \qquad \text{(Eq.2)}$$

Figures 2 and 3 show this correlation graphically for Hong Kong projects. The gradient of the line changes according to a variety of factors, including the EE-EC conversion factor and construction price inflation, but the correlation is likely to remain quite similar. These values are relevant for 2016 prices and should be adjusted downwards in future years to reflect construction price inflation.

For Melbourne, very strong relationships were also found between EE and Cost for new-build projects (r^2 = 0.9315) and refurbishment projects (r^2 = 0.9834). These are shown in Figures 4 and 5. The equations for Melbourne are provided below – where Cost is measured in AUD (millions):

$$EE_N = 5990.1 \times Cost \qquad \text{(Eq.3)}$$

$$EE_R = 4887.3 \times Cost \qquad \text{(Eq.4)}$$

Discussion and Limitations

There is an urgency to move away from the use of carbon as a source of electrical energy. This transition is unlikely to be achieved quickly. International agreements have been made to ensure global warming this century is kept well below 2°C compared to pre-industrial levels (United Nations, 2016). However, recently the United States has withdrawn their commitment, placing these targets in jeopardy (Zhang et al. 2017). Other countries, including Australia, have waived slightly on their commitment to the challenge ahead.

Theoretically, as countries decarbonize, the EE-EC conversion rate moves towards zero. Until then, strategies to reduce the amount of carbon embodied in construction will be of importance, not only in monetary terms, but in order to ensure our planet remains habitable. The constructed environment is clearly a major player in energy demand when the upstream (embodied) and downstream (operational) energy footprint isconsidered over the full life cycle of existing buildingstock.

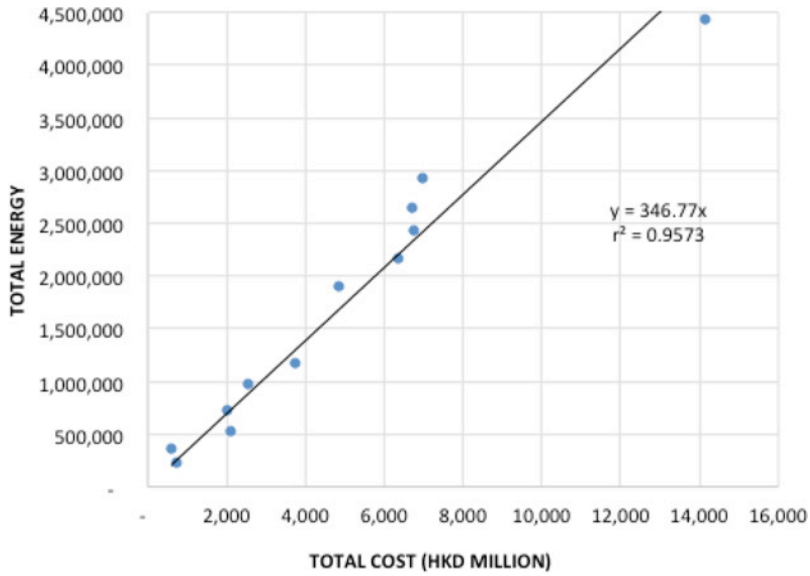

Figure 2 New-build EE versus Cost (Hong Kong)

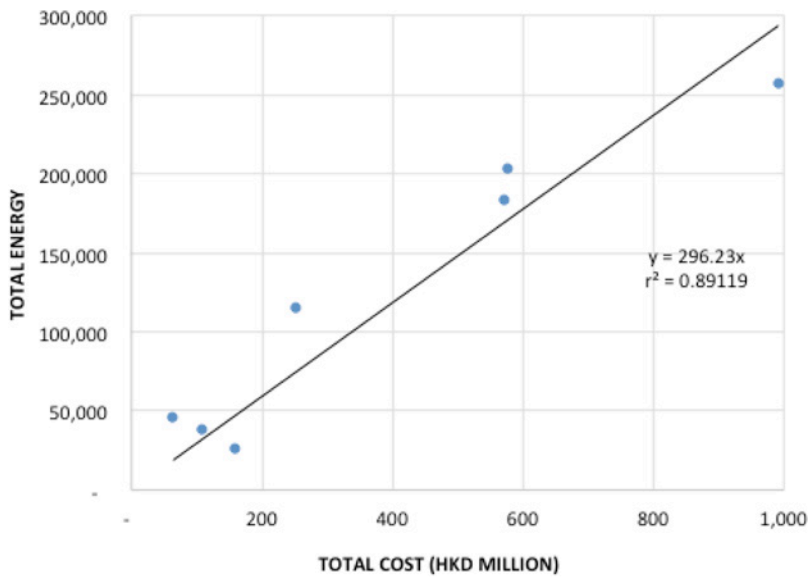

Figure 3 Refurbished EE versus Cost (Hong Kong)

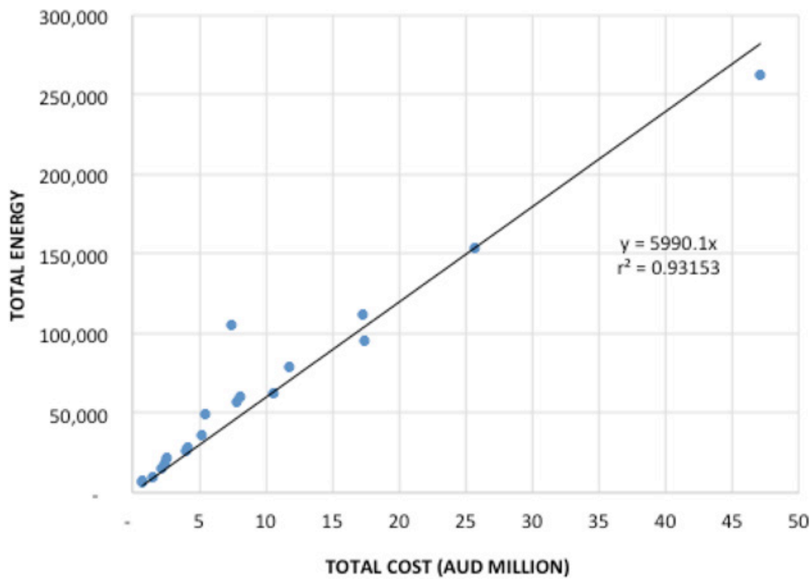

Figure 4 New-build EE versus Cost (Melbourne)

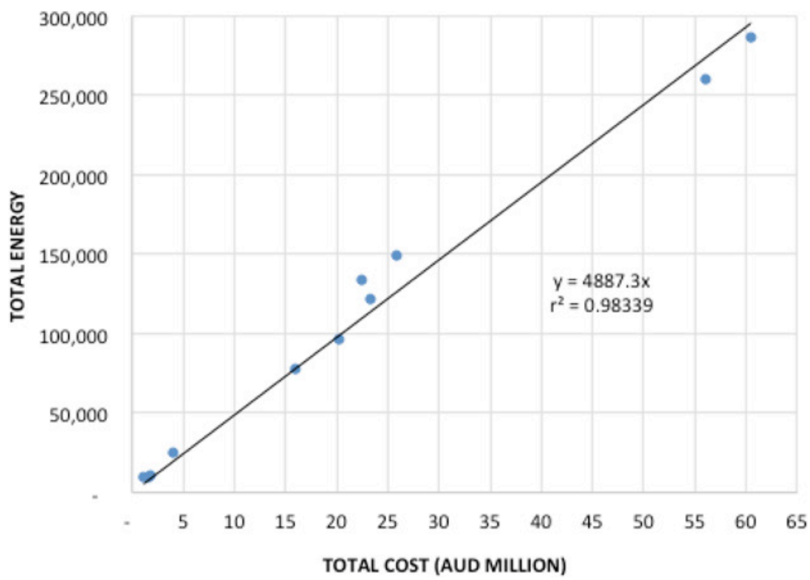

Figure 5 Refurbished EE versus Cost (Melbourne)

Figure 6 combines both new-build and refurbished projects for Hong Kong. The mean for each isrepresented as horizontal and vertical solid lines and computed to determine the likely reduction in EC and Cost per square metre between new-build (blue) and refurbished (red) building work. This is shown as 33% and 22% respectively. The horizontal and vertical dotted lines represent mean EC and Cost prior to removal of outliers, and if not removed would have produced computed reductions of 39% and 50% respectively.

The results make sense, given the correlation between EE and Cost and the direct relationship between EE and EC, demonstrating that refurbished projects can provide both economic and environmental advantage over new-build projects. Their social contribution, however, is a compromise between preserving community history and culture versus

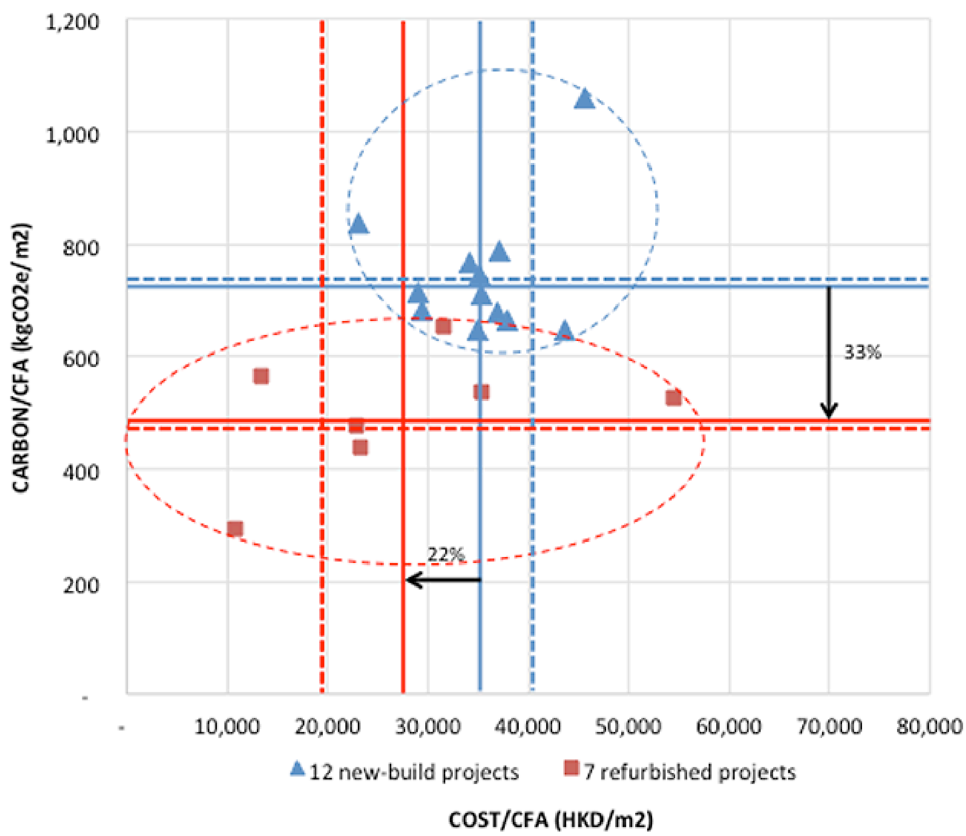

Figure 6 New-build versus Refurbished EC and Cost Comparison (Hong Kong)

progressive improvements to end-user experience through new technology and enhanced design flexibility. The differentialsaving in EC outstrips the differentialsaving in Cost.

A limitation of this finding, however, is the homogenous nature of the projects in the dataset. New-build projects were all high-rise residential apartments. Refurbished projects were nearly all high-rise office space. Leaving the outliers in might be a fairer test.

Figure 7 combines both new-build and refurbished projects for Melbourne. The mean for each is represented as horizontal and vertical solid lines and computed to determine the likely reduction in EC and Cost per square metre. This is shown as 4% and -24% respectively (i.e. refurbished costs were shown to be higher than new-build construction). This result is surprising because it does not reflect the same trend as evident in the Hong Kong data. The lack of saving in EC may be explained if there was a large component of new work (i.e. lack of reuse) within the refurbished projects, and the higher cost for refurbished projects may be due to the labour-intensive nature of the work coupled with the much higher cost of labour in Australia. There were no outliers in the Melbourne data.

Overall, EC per square metreis higher in Melbourne than Hong Kong. This is partially due to the higher EE-EC conversion factor between the two countries and the slight difference between CFA and GFA calculation, but more likely it is a result of the quality of EE intensity data available. The average EC of new-build projects for the Hong Kong study is 745 $kgCO_2e/m^2$. This compares to 1,441 $kgCO_2e/m^2$ for Melbourne. Refurbished projects average 500 $kgCO_2e/m^2$ for Hong Kong and 1,384 $kgCO_2e/m^2$ for Melbourne.All are higher that the

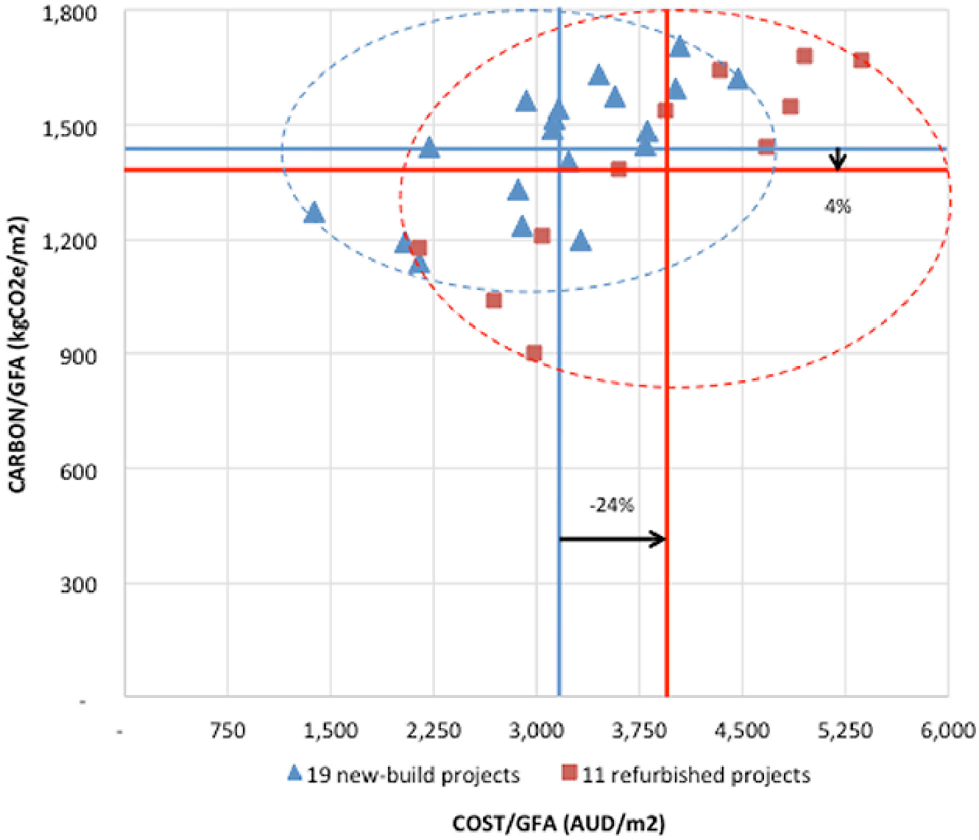

Figure 7 New-build versus Refurbished EC and Cost Comparison (Melbourne)

ECBD averages presented earlier in Figure 1. It should be noted there are inherent and self-declared limitations with the ECBD (CLF 2017:8):

1. The database reports initial embodied carbon of buildings and does not include maintenance, energy use, or end of life impacts, nor building related components such as site work, mechanical/electrical systems and furnishings.
2. It is not appropriate to use this data to make comparative assertions between building types or categories.
3. This database is not a statistically representative sample of current building practices and is weighted to larger, more prominent buildings than those that make up the complete building stock.

In regard to dot point 1 above, ECBD is likely to under-report EC.

Project costs were higher in Hong Kong than Melbourne. Applying a simple exchange rate appropriate to 2016 (1 AUD = 6 HKD), the cost of new-build projects for the Hong Kong study average HKD 35,149/m^2 compared to HKD 18,810/m^2 (AUD 3,135/m^2) for Melbourne. The cost of refurbished projects for the Hong Kong study average HKD 27,358/m^2 compared to HKD 23,232/m^2 (AUD 3,872/m^2) for Melbourne.

However, exchange rates are not the preferred method for comparing international construction performance. Langston (2016) recommended the use of *citiBLOC* (a construction-specific purchasing power parity method) for comparing prices between cities. He indicated that the indices for Hong Kong and Melbourne (actually Sydney) were 4,149 and 2,574 respectively in 2013. This indicates an overall cost premium for Hong Kong of

61.19%. More recent calculations for 2018 show the indices are now 5,317 (Hong Kong) and 2,919 (Melbourne), representing a cost premium for Hong Kong of 82.15% using the same methodology. So, the collected data seems reasonable.

In comparing the EC and Cost performance of two types of projects across two cities, a number of contextual factors have probably affected the results:

1. Generally, the Hong Kong projects were of bigger scale. The average size of new-build projects for the Hong Kong study is 136,475 m2. This compares to 2,862 m2 for Melbourne. Refurbished projects average 15,215 m2 for Hong Kong and 5,280 m2 for Melbourne.
2. Hong Kong projects are generally high-rise while Melbourne projects are generally low-rise. While multi-storey buildings are more cost effective than single-storey, due to efficiencies in expensive foundation and roof elements, this cost effectiveness is eventually replaced by extra costs in lifting materials to high floors, vertical transportation, and the additional expense of structural elements and façade treatment.
3. Melbourne new-build projects are largely commercial (schools, hospitals, office buildings, civic buildings, etc.) compared to residential apartments in Hong Kong. The Hong Kong dataset generally is more homogenous.
4. The cost of construction labour, based on general unskilled worker hourly rates sourced from Turner and Townsend (2018), is higher in Melbourne (AUD 68/hr) than Hong Kong (HKD 115/hr). Refurbished projects are likely to be more labour-intensive than new-build projects.

Therefore, the above issues, which underscore temporal, geographical and cultural differences between the Hong Kong and Melbourne projects, need to be considered as a further limitation of this study. The reasons for differences in EC and Cost that have been identified herein are beyond the scope of this paper, but certainly deserving of future research investigations.

Conclusion

Comparing construction performance between different countries is always fraught with difficulty. In this study, project size, height, usage and labour cost variances (which are linked to productivity) all play a part in the discovered results. What is clear, is that there is a very strong relationship between EE and Cost for both new-build and refurbished projects in each city suggesting that the former can be predicted from the latter. There is also some evidence, and certainly logic,to infer that refurbished projects have lower EC/m^2 than new-build projects. Nevertheless, as the world moves slowly towards less reliance on fossil fuels as an energy source, as it must, the relevance of EC is constantly reducing. Perhaps in the future, embodied pollution may be a hotter topic for researchers to explore. Waste from building demolition of existing structures to make way for new-build developments may need to be given more consideration, with more emphasis placed on recycling and adaptive reuse strategies.

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